varieties can also help shift pollution-impacted, declining forests into more productive forests. However, in recent years forests have demonstrated a surprising ability to recover all by themselves once the pollutant source is eliminated.

In recent years forests have demonstrated a surprising ability to recover once the pollutant source is eliminated. What was once thought to result in total destruction of forests in highly polluted regions is now understood to be yet another disturbance similar to fires or floods from which forests will recover over time. There are exceptions, such as sites heavily contaminated by metals; these areas will require more active remedial action. However, the annihilation of native forests due to air pollution, predicted during the 1970s and 1980s, has for the most part not occurred. Are these recovering forests the same before and after high pollution events? Probably not, but all landscapes are constantly responding to environmental conditions in ways that are difficult to quantify. It becomes the job of the forester and society to determine how air pollution effects are moderated so that all the resources that forests have to offer remain intact.

See also: **Environment**: Carbon Cycle; Impacts of Elevated CO_2 and Climate Change. **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Health and Protection**: Biochemical and Physiological Aspects; Diagnosis, Monitoring and Evaluation. **Site-Specific Silviculture**: Reclamation of Mining Lands; Silviculture in Polluted Areas.

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Carbon Cycle

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Introduction

The forest environment carbon cycle can be viewed at a number of scales. Measurements can be made at the scale of an individual leaf or tree, stand-scale measurements can be made, and models can be developed that examine forest-level, regional, and global carbon cycles. The role of the forest in the global carbon cycle has become increasingly important as it is realized that forests and forestry have a role to play in mitigating the so-called greenhouse effect. This article examines the sources, sinks, and fluxes of carbon as they relate to forests and then places this information within the context of global change. Finally, the potential contribution of forests to the mitigation of climate change is assessed.

The Global Carbon Cycle

The main components of the natural global carbon cycle are the sources, sinks, and fluxes between the land, oceans, atmosphere, and geological reservoirs. Current estimates suggest that the atmosphere contains about 730 Pg C, the land 2000 Pg C, the oceans 38 000 Pg C, and that an unknown amount remains in geological reservoirs. The greatest natural flux (120 Pg C per year) is between the land and the atmosphere, with a smaller flux occurring between the atmosphere and the oceans (90 Pg C per year). Estimates of the sizes of the different carbon pools are given in **Table 1**. In terms of fluxes, the carbon cycle can be seen as an approximate balance between the processes of photosynthesis by plants and respiration by plants, animals, and microbes. It is the variations on either side of an exact balance between photosynthesis and respiration that cause natural variations in the global carbon pools, supplemented by anthropogenic activities, such as the clearing of forests and the burning of fossil fuels,

Table 1 Estimates of terrestrial carbon stocks and net primary productivity published by the Intergovernmental Panel on Climate Change

Biome	*Area (10^9 hectare)*	*Global carbon stocks (Pg C)*		
		Plants	*Soil*	*Total*
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas and grasslands	2.25	66	264	330
Temperate grasslands and shrublands	1.25	9	295	304
Deserts and semideserts	4.55	8	191	199
Tundra	0.95	3	121	127
Croplands	1.60	6	128	131
Wetlands	0.35	15	225	240
Total	15.12	466	2011	2477

which cause further changes (both in the balance between photosynthesis and respiration and in the total carbon fluxes).

The Forest Carbon Cycle

All higher plants take up carbon dioxide. Globally, the amount of CO_2 that is dissolved in leaf water has been estimated to be 270 Pg C per year, representing more than one-third of all the CO_2 stored in the atmosphere. Most of this carbon leaves the plants without being involved in photosynthesis. The fraction that remains and which is converted from CO_2 to carbohydrate is known as the gross primary production (GPP). The total amount of terrestrial GPP has been estimated at 120 Pg C per year. Approximately one-half of this is converted back to CO_2 by autotrophic respiration. Autotrophic respiration (often abbreviated to R_A) can be divided into two distinct processes: maintenance respiration (R_M), which is the respiration that is required for a plant to maintain its basic physiological processes and thus to survive, and construction respiration (R_C), which is the respiration that is needed for the plant to build new structures such as leaves, roots, the stem, flowers, and other organs. Autotrophic respiration therefore refers only to plants.

Scaling up to the ecosystem level, the difference between GPP and autotrophic respiration is termed net primary production (NPP). There are many measurements available for NPP, and the total amount of NPP globally has been estimated to be about 60 Pg C per year. Almost all of this carbon is returned to the atmosphere through heterotrophic respiration (R_H), which is the respiration of organisms that break down the products of net primary production, including both herbivores and decomposers, and through fires. Within forest ecosystems, fires can be a particularly important mechanism for the return of carbon to the atmosphere, with a global estimate of 936 Tg C being released annually by forest fires. However, the reliability of the data used to derive this estimate is very questionable. Where data are available, the figures suggest that fire is of major importance. For example, the 1987 fires in Indonesia, which burnt both above-ground biomass and below-ground peat, are estimated to have released between 0.81 and 2.57 Pg C, equivalent to 13–40% of the global annual emissions of fossil fuels. This figure is higher than the global estimate, as it includes the carbon released by the below-ground burning of peat. If only the above-ground vegetation is included, then the figure was reduced to 50 Tg C.

Heterotrophic respiration is especially important, as it is largely responsible for the return of organically bound carbon to the atmosphere. Much of this occurs in soils or on the soil surface, with the rate of breakdown being controlled by a number of different factors, including climate, chemical composition of the plant matter, soil conditions, and others. The microbial biomass and soil detritus tends to break down quite quickly (within 10 years), whereas modified soil organic carbon may take much longer (100 years or more, depending on the climate). Turnover times for forest litter vary from less than 6 months in some tropical forests to over 350 years in boreal coniferous forests. In many forests, the rates of breakdown have been influenced by management practices, and management presents an opportunity to control in part the carbon in forests.

The biomass pools in a forest can be divided into the above- and below-ground tissues of plants, woody debris, the forest floor, the mineral soil, and the tissues of heterotrophic organisms. The proportions in each of these pools vary dramatically, depending on the type of forest, with figures for the

Table 2 Forest volume and above-ground biomass by region, as published by the UN Food and Agriculture Organization

Region	*Forest area (million hectare)*	*Volume*		*Biomass*	
		By area (m^3 hectare^{-1})	*Total (Gm^3)*	*By area (t hectare^{-1})*	*Total (Gt)*
Africa	650	72	46	109	71
Asia	548	63	35	82	45
Oceania	198	55	11	64	13
Europe	1039	112	116	59	61
North and Central America	549	123	67	95	52
South America	886	125	111	203	180
Total	3869	100	386	109	422

above-ground biomass being presented in **Table 2**. Approximately 50% of the dry biomass of a tree is thought to consist of carbon, although carbon removed from the atmosphere of the tree may also be transferred to the soil carbon pool through litterfall. The actual amount sequestered by an individual tree will depend on the species, the growing conditions, and its environment. The environment is important: in urban areas, the leaves or needles shed by a tree are often removed, preventing uptake into the soil.

A mature forest is generally considered to be 'carbon-neutral.' This means that it releases as much carbon as it absorbs. This assumption is based on looking at the carbon balance over a fairly extensive area of forest, as local stand dynamics can result in substantial changes in the carbon balance as the forest is disturbed and regrows. Using the terms described above, NPP should more-or-less equal R_H. While this may be the case for some mature forests, more often forests are in a state of dynamic equilibrium, with some net carbon either being gained or lost from the forest ecosystem. This is termed the net ecosystem production (NEP); measurements of NEP range from 0.7 to 5.9 Mg C hectare^{-1} year^{-1} for tropical forests, 0.8 to 7.0 Mg C hectare^{-1} year^{-1} for temperate forests, and up to 2.5 Mg C hectare^{-1} year^{-1} for boreal forests. The rates are very variable, and in some areas there may be negative NEPs in particular years.

The NEP represents only the difference between NPP and R_H, and does not take into account carbon losses through fire, erosion, and other processes. The overall figure of relevance to global forest carbon cycles is the net biome production (NBP), which takes into account all the processes of carbon gain and loss from the terrestrial biosphere. This has been estimated at -0.2 ± 0.7 Pg C year^{-1} during the 1980s and -1.4 ± 0.7 Pg C year^{-1} during the 1990s. The negative values for these flux estimates indicate that the land is acting as a sink for atmospheric carbon.

While the figures for global NPP, NBP, and R_H all appear to be given with some certainty, considerable care should be taken over their interpretation. Most figures are based on models, and the underlying quality of the data used to draw those assumptions and build the models is not always very good. This is particularly true in the case of forests, where great reliance is placed on the Forest Resource Assessment of the UN Food and Agriculture Organization. The quality of this inventory of the world's forests has improved with each successive inventory, but major data quality problems remain, particularly in the tropical countries and Russia. For example, emissions of carbon associated with forest fires in Russia are very uncertain, with information on both the extent and severity of forest fires in Siberia being very unreliable.

Despite these difficulties, there are increasing numbers of indications that carbon stocks in the world's forests may be increasing. In the tropics, data from permanent sample plots indicate that tree growth is increasing, although the flux is more than balanced by losses caused by deforestation. In temperate and boreal forests, an increasing forest area has been accompanied by increasing carbon stocks in existing forests. In some regions, these trends have been present for some time. In the northern hemisphere, the regrowth of forests following the deforestation of the eighteenth and nineteenth centuries is estimated to be responsible for the uptake of 0.5 ± 0.5 Gt C year^{-1}. In other areas, such as the tropics and some temperate regions, the trend appears to be new.

Global Increases in CO_2

Over the past 200 years, the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have been increasing at an exponential rate. These three gases, together with a range of others (particularly the halocarbons), are known as greenhouse gases. The term is used because the gases are able to absorb some of the longwave radiation that is emitted from the earth, resulting in an increase in the temperature of the atmosphere, the so-called 'greenhouse effect.' Since 1750, atmospheric CO_2 concentrations have increased from the preindustrial concentration of 280 parts per million (ppm) by 31%, and current concentrations (367 ppm in 1999) are higher than at any time in the last 400 000 years. Concentrations of CH_4 have increased 151% since 1750, and are also unprecedented within the past 400 000 years, whereas concentrations of N_2O have increased by 17%. The past history of atmospheric N_2O concentrations is less certain than for CO_2 or CH_4, and it is only possible to state that current N_2O concentrations have not been exceeded within the past 1000 years. In contrast to the other greenhouse gases, many of the halocarbon gases that are both greenhouse gases and ozone-depleting have been stable, decreasing or increasing more slowly since 1995, when the Montreal Protocol and its amendments introduced controls on their emissions. They have been substituted by a number of other gases, such as CHF_2Cl and CF_3CH_2F, which are not ozone-depleting, but which are greenhouse gases. These, together with synthetic compounds that are also greenhouse gases, such as perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6), have been increasing in the atmosphere.

Atmospheric concentrations of these gases have varied considerably in the past, providing one of the reasons to question the cause of the current increase in concentrations. However, the rate of change in CO_2 concentrations appears unprecedented, certainly within the past 20 000 years. The preindustrial and recent (1998) concentrations of selected greenhouse gases are given in **Table 3**.

Table 3 Greenhouse gas concentrations in pre industrial times and currently

Gas	*Preindustrial*	*1998*
CO_2	*c.* 280 ppm	365 ppm
CH_4	*c.* 700 ppb	1745 ppb
N_2O	*c.* 270 ppb	314 ppb
CFC-11 (chlorofluorocarbon 11)	zero	268 ppt
HFC-23 (hydrofluorocarbon-23)	zero	14 ppt
CF_4 (perfluoromethane)	40 ppt	80 ppt

The Intergovernmental Panel on Climate Change (IPCC) is a group of government-appointed scientists responsible for looking into the nature, causes, and extent of climate change. They have reached a broad consensus that the increase in CO_2 and other gases is the result of anthropogenic activities, and that the increase is at least in part responsible for the observed increase in global average surface temperatures of $0.6 \pm 0.2°C$ over the past 100 years. It is likely that the 1990s was the warmest decade and 1998 was the warmest year in the northern hemisphere in the last 1000 years, and the IPCC has concluded that most of the observed warming over the past 50 years is likely due to increased greenhouse gas concentrations in the atmosphere.

The influence of different types of forcing factors on global temperatures is calculated using the concept of radiative forcing. The forcing is a measure (expressed in $W\,m^{-2}$) of the extent to which any particular factor influences the incoming and outgoing energy within the earth–atmosphere system. If the forcing is positive, then it results in an increase in temperature. Conversely, a negative forcing results in a lowering of temperature. The radiative forcing of different greenhouse gases is shown in **Table 4**. These figures need to be placed in the context of other forcing factors. For example, the radiative forcing associated with the burning of biomass is estimated to be $-0.2\,W\,m^{-2}$ (indicating a cooling effect), as the aerosols prevent energy from reaching the earth's surface.

During the period 1980–2000, approximately 75% of the CO_2 emissions were from the burning of fossil fuels, whereas the remainder (estimates range from 10% to 30%) was the result of land-use changes, particularly deforestation. Just over half of the emissions of CH_4 are from anthropogenic sources (such as fossil fuels, rice cultivation, cattle, and landfills), whereas only a third of current N_2O emissions are anthropogenic (sources include the chemical industry, cattle feed lots, and agricultural soils). The cumulative carbon losses occurring as a result of land use and management changes have been estimated to be between 180 and 200 Pg C. The loss of forests has been the primary factor, leading to terrestrial carbon emissions since 1850, amounting to about 90% of the total emissions.

Historical land-use changes have certainly had a major impact on the global carbon budget. Data collected by the United Nations Food and Agriculture Organization between 1990 and 2000 suggest that about 15 million hectares of natural forest are lost annually, although the data are very unreliable. This is in part compensated by a natural expansion of forest by 1 million hectares annually, and establishment of about 2 million hectares of forest plantations annually in the tropics. The greatest losses (42% of the total) occur in Latin America, with the proportions in Africa and Asia amounting to 31% and 27%, respectively. The land-use changes and forestry operations in the tropics are estimated to be releasing between 1.1 and $1.7\,Gt\,C\,year^{-1}$ (during

Table 4 Radiative forcing of greenhouse gases from 1750 to 2000

Greenhouse gas	*Radiative forcing*
CO_2	1.46 $W m^{-2}$
CH_4	0.48 $W m^{-2}$
Halocarbons	0.34 $W m^{-2}$
N_2O	0.15 $W m^{-2}$
Total	2.43 $W m^{-2}$

the mid-1990s) although, again, the estimates are very approximate and based on incomplete data. The area of forested land in the temperate regions is, however, increasing by about 3 million hectare annually. This means that there was a net annual loss of forests in the period 1990–2000 of about 9.4 million hectare, equivalent to a biomass loss of about 1.6 Gt annually. This last figure should be treated with caution, as it is based on changes in forest area alone. There are also changes occurring within forests, such as the increase in productivity described above. Outside the tropics, a biomass gain within the forest of about 0.9 Gt occurred annually in the period 1990–2000. No equivalent figure is available for tropical forests.

Forests and the 'Greenhouse Effect'

The increase in global mean temperature is important as it will have a wide range of effects. For example, increased temperatures are leading to the loss of ice from glaciers and icecaps. At the same time, the increase in the temperature of the surface layers of the earth's oceans is resulting in thermal expansion of the surface waters. Combined, these processes have resulted in an increase in sea-level, with major potential consequences for low-lying land areas. In the Pacific region, several island groups are now threatened with submersion, with sea levels expected to increase by between 0.09 and 0.88 m between 1990 and 2100.

A number of potential solutions have been proposed, and an international mechanism to encourage solutions, the Kyoto Protocol, was agreed in December 1997. The Kyoto Protocol stated that industrialized countries would, by 2008–2012, reduce their combined greenhouse gas emissions by 5.2% relative to their 1990 emissions. Individual countries have specific targets, and some countries can even increase their emissions by the year 2012. A number of strategies can be adopted to reduce emissions, including increased energy efficiency, reduction in energy demand, and implementation of alternative technologies. In addition, several short-term steps can be taken through the development of carbon sinks.

The focus of the Kyoto Protocol and its amendments has been on CO_2. This is because CO_2 is the dominant human-influenced greenhouse gas, accounting for a radiative forcing of 1.46 $W m^{-2}$, or 60% of the radiative forcing of all the long-lived greenhouse gases. The rate of increase in the gas is variable, and in the 1990s, it ranged from 0.9 to 2.8 ppm $year^{-1}$, or 1.9 to 6.0 Pg C $year^{-1}$. The variation seems to be related to the occurrence of El Niño events, with higher rates of increase occurring in years with marked El Niño events (due to reduced terrestrial uptake).

Trees to Mitigate CO_2 Increases

The potential of forests to reduce the rate of increase in atmospheric CO_2 has been the subject of much debate, especially within the context of the Kyoto Protocol to the United Nations Framework Convention on Climate Change. At issue has been the extent to which countries should be allowed to offset their CO_2 emissions through the enhancement of sinks (which partly avoids the difficult issue of directly reducing CO_2 emissions). In addition, the many uncertainties associated with the quantification of the forest carbon sink has caused problems. The Kyoto Protocol (Articles 3.3 and 3.4) specifically recognized forests as carbon sinks, but it was not until November 2001 that some of the definitions were finally established (the Marrakesh Accords).

The increase in atmospheric CO_2 concentrations can be clearly linked to fossil fuel burning and to land-use change. The land-use change of greatest relevance is normally considered to be deforestation. Unfortunately, estimates of deforestation rates are extremely unreliable, making it difficult to determine precise figures. However, the net release of CO_2 from terrestrial sources, which amounted to between 0.6 and 2.5 Pg C $year^{-1}$ during the 1980s, has been attributed to deforestation in the tropics. A related problem is deforestation in high latitudes, where models of deforestation have suggested that the conversion of snow-covered forests to snow-covered open areas has resulted in an increase in the albedo (reflected energy), causing a cooling effect in the order of -0.2 ± 0.2 $W m^{-2}$. Reducing the rate of this deforestation would clearly have an impact on the global carbon cycle.

Trees are seen as a potential means to sequester carbon. This is based on the idea that a one-time benefit can be obtained by planting forests in areas where forests have previously been lost. Tree plantations in the boreal, temperate, and tropical zones are thought to have sequestered about 11.8 Gt C, with an annual sequestration rate of 0.2 Gt C $year^{-1}$. The IPCC has estimated that slowing the rate of deforestation combined with the promotion of natural forest regeneration and afforestation could increase terrestrial carbon stocks in the period 1995–2050 by between 60 and 87 Pg C. In Brazil alone, a reduction in the rate of deforestation by 50% could conserve as much as 125 Mt C $year^{-1}$.

A potentially much more valuable function of forests is as a supply of biomass for burning in power generation. While the carbon stored in the wood is immediately released into the atmosphere, the benefits are gained when the power that is generated replaces power generated from fossil fuels. This approach has been strongly advocated in some European countries, but there is still a need to look at the full costs of the power generation (i.e., including the carbon costs associated with the construction of the power generation plant and with the development and growth of the forest).

In addition to such direct methods, the IPCC has identified a number of silvicultural and management techniques that might be used to enhance carbon mitigation. These include fire prevention and control, protection against pests and disease, changes to rotation lengths, control of stand density, enhancement of nutrient supply, control of the water table, selection of useful species and genotypes, use of biotechnology, reduced regeneration delays, selection of harvesting methods such as reduced-impact logging, recovery of degraded forest, management of logging residues, recycling of wood products, increased use of wood, and efficiency of the conversion process from wood to products, and the establishment and maintenance of forest reserves. These methods all provide means by which the forest sector could contribute to the global effort to reduce anthropogenic impacts on the global carbon cycle.

See also: **Environment**: Impacts of Elevated CO_2 and Climate Change. **Mensuration**: Tree-Ring Analysis. **Non-wood Products**: Energy from Wood. **Tree Physiology**: A Whole Tree Perspective; Forests, Tree Physiology and Climate.

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Terminology

Pg C Petagrams of carbon (1 Pg C = 1 Gt C = 1000 Mt C = 10^{15} g C).

Tg C Teragrams of carbon (1 Tg C = 1 Mt C = 10^6 tonnes C = 10^{12} g C).

Mg C Megagrams of carbon (1 Mg C = 10^6 g C = 1 tonne C).

Gt C Gigatonnes of carbon (1 Gt C = 10^9 tonnes C = 3.7 Gt of carbon dioxide).

Mt C Megatonnes of carbon (1 Mt C = 10^6 tonnes C).

Impacts of Elevated CO_2 and Climate Change

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Introduction

Forests have always been sensitive indicators of climate change. Tree pollen, preserved in lake sediments and bogs, provides a record of how tree species migrated northwards as warming occurred after the retreat of ice about 12 000 years ago. Many tree species reached a maximum northern limit in the